Investigation of Incident at Windscale in 1957 using a Preliminary Emission Scenario

Author: Catrina Johnson, Senior Applied Scientist

Prepared for: British Nuclear Fuels plc

Date: 22.04.05

MetO ref: M/BO/P105

The information in this report is provided in good faith and is believed to be correct, but the Met. Office can accept no responsibility for any consequential loss or damage arising from any use that is made of it.

Met Office, FitzRoy Road, Exeter, Devon EX1 3PB.
Tel 0870 900 0100 Fax +44 (0)1392 885681 www.metoffice.gov.uk

Direct contact: email: catrina.johnson@metoffice.gov.uk Tel 01392 885177

Executive Summary

In October 1957 there was a fire in a nuclear reactor at the Windscale Works, Sellafield, Cumbria. This resulted in the uncontrolled release of radionuclides into the atmosphere via a 120m stack. *Crabtree (1959)* estimates the likely amount of iodine-131 released during the 1957 incident. Crabtree made a number of assumptions, the first one being that the maximum boundary layer height was 1500m. He also assumed that all of the radioactivity in the plume crossed the line joining Liverpool and Flamborough Head and that the plume was only 120km wide as it crossed. This implies that the plume did not extend far to the east of Doncaster and therefore not over the North Sea. Finally, he assumed that the average windspeed perpendicular to the line during the passage of the plume was 5.0ms^{-1}. The preliminary release scenario (Table 1) of the incident combines data in *Weerasekera (2004)* with supplemental data supplied as a personal communication from John Garland (an expert on environmental radioactivity). The Met Office's long-range Lagrangian dispersion model - the Numerical Atmospheric dispersion Modelling Environment (NAME), has been used to model this scenario and to assess the assumptions made in *Crabtree (1959).*

The aim of this analysis is to examine the adequacy of the assumptions that underline Crabtree's estimate of the emission of Iodine-131. The outcome will be used by others to better determine the emission source profile. Results showing the percentage of material over the UK and within the boundary layer are presented. A brief comparison between observations and the gridded ERA-40 data (used within this modelling study) is provided. Crabtree's assumption regarding boundary layer height appear to be valid though it is clear that material likely extended further east than he assumed, extending over the North Sea.

1.0 Introduction

1.1 The Incident

An incident at the Windscale Works nuclear facility at Sellafield (on the coast of Cumbria, northwest England - 54° 25.0'N 3° 30.2'W) resulted in an uncontrolled release of radionuclides to the atmosphere (*Penney (1957), Arnold (1995)*). A fire developed in the No.1 Pile (an open-circuit air-cooled and graphite moderated metallic uranium nuclear reactor) on the 10th October 1957 and gradually increased in intensity. It was eventually brought under control some time on the 11th October. The subsequent dispersion and eventual deposition of isotopes resulted in activity being detected over parts of England and Wales and other areas of Northern Europe (*Chamberlain (1959, 1996), Chamberlain and Dunster (1958), Crabtree (1959), Stewart and Crookes* (*1958)*). An extensive programme of environmental measurements made during and after the incident included samples of soil, herbage, water and food (*Dunster et al.(1958), Crick and Linsley (1984)*).

Although some of the details about the sequence of events leading to the fire are still not clear, certain facts have been established. Overheating in the pile core was detected early on the 10th October. Later on, enhanced radioactivity readings were detected on site and part of the reactor was found to be on fire. As soon as activity was recorded on site an environmental survey was initiated. Action was also taken to create a firebreak within the reactor core to limit the spread of the fire. At around 00:00 on the 11th October the decision was made to use water on the fire. This was eventually used at 09.00 on the 11th October and applied for thirty hours. The fire was finally extinguished by midday on the 11th October. A detailed account of the incident can be found in *Arnold (1995).*

1.2 Model Details

The Met Office's NAME model is used to simulate the medium and long-range transport of a range of airborne pollutants. The model provides estimates of instantaneous air concentrations and time integrated air concentrations (TIAC), together with estimates of the deposition of pollutants to the ground by both wet and dry deposition processes. Wind fields and other meteorological data are used to drive NAME. These are generally obtained from global, regional and mesoscale versions of the Met Office's Numerical Weather Prediction (NWP) Model – also referred to as the Unified Model. NWP datasets were not available for use in this study as they are only available from 1995. However, the European Centre for Medium Range Forecasting's ERA-40 dataset does cover this time period and was therefore used in the study. A description of the ERA-40 dataset is given in section 3.0.

NAME, a Lagrangian particle model, simulates the release and spread of pollutants by releasing large numbers of hypothetical particles into a model atmosphere. Each of these particles carries with it a mass of the species being modelled, reflecting the released quantity of emissions or chemical conversions. These particles are then advected in three dimensions by the model wind field and parameterised atmospheric turbulence.

As the particles are transported in time and space, they may experience changes in the mass they carry. The processes by which material is lost from the atmosphere include wet and dry deposition to the ground, radioactive decay and chemical reactions. Within the model these losses are applied on a particle basis, i.e. the mass of each particle is reduced each timestep, and for deposition processes the depleted mass added to surface deposition maps. Particles are never removed by deposition *in toto*, and lost to the integration - they simply lose a proportion of the mass they carry.

Within NAME there is an option to apply plume rise. This was utilised in this study to best simulate the conditions produced by the heat of the fire. Emissions often have substantial vertical velocities or are hot compared with the surrounding ambient air. These momentum and buoyancy effects cause the emitted plume to rise, increasing the effective source height and, in the main, reducing nearby ground level concentrations. The NAME plume rise scheme solves an integral model based on the governing conservation equations of mass, momentum and heat. Mixing of ambient air into the plume is modelled throughout the plume rise process using the concept of an entrainment velocity. Turbulence,

due to the plume rise process, is parameterised within the model. More details are contained in *Webster et al. (2002).*

2.0 Methodology

2.1 Release Characteristics

The following table summaries the emissions applied within the simulation. The temperature and exit velocity for the critical period around 10:00 on 11/10/57, when emission rates were maximum are taken from *Weerasekera (2004)*. Other data were given by John Garland in a personal communication.

Note that a total of 100 units of radioactivity were released over the period.

Beginning Date and time	Exit Temperature (K)	Release units per sec	Exit velocity (m/s)
10/10/57 16:30	398	0.0000639	3.7
10/10/57 17:30	403	0.0000639	3.8
10/10/57 18:30	408	0.0000639	3.9
10/10/57 19:30	413	0.0025560	4.0
10/10/57 20:30	418	0.0025560	4.1
10/10/57 21:30	423	0.0025560	4.2
10/10/57 22:30	426	0.0025560	4.2
10/10/57 23:30	428	0.0025560	4.3
11/10/57 00:30	441	0.0025560	4.5
11/10/57 01:30	454	0.0025560	4.7
11/10/57 02:30	467	0.0000639	4.9
11/10/57 03:30	480	0.0000639	5.1
11/10/57 04:30	493	0.0000639	5.3
11/10/57 05:30	506	0.0006389	5.5
11/10/57 06:30	519	0.0006389	5.7
11/10/57 07:30	533	0.0006389	5.8
11/10/57 09:00	1163	0.0006389	19.2
11/10/57 10:00	533	0.0031940	6.4
11/10/57 10:30	513	0.0031940	6.0
11/10/57 11:30	493	0.0000639	5.6
11/10/57 12:30	473	0.0000639	5.2
11/10/57 13:30	453	0.0000639	4.8
11/10/57 14:30 until 15:30	433	0.0000639	4.4

Table 1 - Release scenario

Release height :120m

Stack diameter : 7.0m

2.2 Modelled Receptor Grid

The model grid extended from 51.0ºN to 56.7ºN latitude and 8.0ºW to 4.7ºE longitude, covering the central area of the UK, with a grid spacing of 0.045º latitude and 0.091º longitude. Also included were a number of specific receptor points along a line from Liverpool to Flamborough Head extending into the North Sea up to 4.0ºE longitude. Detailed time series information are generated for these locations within the model run. Figures 2 to 19 show the extent of the receptor grid.

3.0 Meteorology

NAME calculated boundary layer height within this study using the wind and temperature profiles from the ERA-40 dataset and applying a mixture of Richardson number and parcel top method.

One of the many initiatives undertaken by the European Centre for Medium-range Weather Forecasts (ECMWF) was the 'ECMWF Re-Analysis' or the ERA-40 project, *Gibson et al (1997).* The objectives of this project were to produce and promote a comprehensive set of global analyses that described the state of the atmosphere, land and ocean wave conditions from mid 1957 to 2001 (incorporating the earlier ECMWF re-analysis period used for ERA-15, 1979 – 1993).

The range of observational sources re-assimilated in order to initialise the model, ordinarily includes:

- the World Meteorological Organisation (WMO) Global Telecommunications System (GTS), for which ECMWF has held data since 1979;
- satellite systems ;
- project experiments such as the First Global GARP Experiment (FGGE) and the ALPine EXperiment (ALPEX);
- radiosondes;
- ships;
- buoys;
- aircraft ;
- sea surface temperature and sea ice cover (used for external forcing fields).

Note that some of these sources were not available for 1957.

The model output data is provided on a three-dimensional global grid. The model used for ERA-40 has a 'spectral' analysis and forecasting technique (that is, based on Fourier modes rather than a computational mesh). It is stored in T159 spherical harmonic field format, corresponding to a grid spacing of approximately 1.125° latitude / longitude, and has 60 vertical levels. At this resolution local effects such as coastal effects (e.g. land and sea breezes) will not be accounted for. The complex vertical structure contains a grid following the terrain close to the surface but gradually adapting to pressure levels at higher altitudes. The ERA-40 data assimilation and forecast suite produces four analyses per day for 00, 06, 12 and 18 UTC.

The six hourly analysis data was used by the NAME model in this study.

http://www.ecmwf.int/publications/library/do/references/list/192 gives more references for the ERA-40 project.

A number of steps of interpolation are employed in order to gain the spatial and temporal resolution required by the NAME model. Errors will be inherent in the assimilation process adopted within the ERA-40 analysis. NAME further interpolates this data in time and space to determine meteorological conditions at a particle location. Tables 2, 3 and 4 illustrate some typical differences to be found between ground based observations and the ERA-40 data. The first station is Silloth which is located to the north of Windscale in a similar coastal location. The second is Watnall which is close to Nottingham in an inland location.

		Observed	ERA-40	Observed	ERA-40	Observed	ERA-40	Observed	ERA-40
Date	Hour (GMT)	Mean wind Direction (deg true)	Mean wind Direction (deg true)	Mean wind speed (ms^{-1})	Mean wind speed (ms^{-1})	Temperature (°C)	Temperature (°C)	Actual cloud (octas)	Actual cloud (octas)
10/10/57	18	Calm	228	Calm	0.7	11.7	12.5	8	4
10/10/57	21	Calm	250	Calm	1.1	11.1	11.7	8	6
11/10/57	00	Calm	285	Calm	1.4	10.6	10.9	8	7
11/10/57	03	250	291	2.6	1.6	11.7	10.8	8	5
11/10/57	06	310	303	3.1	1.7	11.1	10.7	7	4
11/10/57	09	280	306	3.1	2.0	10.6	11.5	1	4
11/10/57	12	240	301	4.1	2.3	13.3	12.3	5	4
11/10/57	15	240	294	2.1	2.4	13.9	11.8	5	3
11/10/57	18	270	279	3.6	2.6	11.7	11.2	3	2
11/10/57	21	280	274	2.6	2.2	7.8	10.5	6	2
12/10/57	00	220	255	3.1	1.9	6.1	9.8	7	2
12/10/57	03	200	244	2.1	2.0	6.7	9.9	7	4
12/10/57	06	200	235	3.6	2.1	7.8	10.0	7	8
12/10/57	09	210	238	3.1	2.5	10.0	11.2	7	8
12/10/57	12	230	237	6.7	2.8	12.8	12.4	7	8
12/10/57	15	230	233	4.6	3.0	12.2	12.0	7	4
12/10/57	18	230	234	6.7	3.2	11.7	11.5	7	5
12/10/57	21	220	239	7.2	3.3	12.2	11.4	7	5

Table 2 – Comparison of observed and ERA40 met data at Silloth (54.87°N Latitude 3.364°W Longitude, Station altitude: 8m)

Date	Hour (GMT)	Observed Mean wind Direction (deg true)	ERA-40 Mean wind Direction (deg true)	Observed Mean wind speed (ms^{-1})	ERA-40 Mean wind speed (ms^{-1})	Observed Temperature (°C)	ERA-40 Temperature (°C)	Observed Actual cloud (octas)	ERA-40 Actual cloud (octas)
10/10/57	18	90	202	2.1	1.4	13.9	15.2	7	3
10/10/57	21	Calm	214	Calm	1.5	12.8	14.1	7	5
11/10/57	00	230	240	2.6	1.5	12.8	13.0	8	6
11/10/57	03	250	243	1.0	1.3	12.2	12.6	8	5
11/10/57	06	300	283	2.6	1.0	10.6	12.2	7	4
11/10/57	09	250	303	2.6	1.4	12.2	13.7	8	4
11/10/57	12	230	308	4.6	1.9	13.9	15.1	8	3
11/10/57	15	Calm	309	Calm	1.4	13.9	13.2	3	3
11/10/57	18	300	307	4.1	0.9	11.1	11.3	1	3
11/10/57	21	330	307	3.6	1.3	8.3	8.5	1	2
12/10/57	00	310	283	2.6	1.5	7.2	5.7	1	1
12/10/57	03	220	252	0.5	1.1	3.9	4.2	2	4
12/10/57	06	Calm	222	Calm	0.7	3.9	2.7	3	7
12/10/57	09	Calm	222	Calm	0.7	6.1	8.1	6	4
12/10/57	12	190	208	1.5	0.8	13.3	13.6	3	2
12/10/57	15	220	200	3.1	1.0	13.3	12.0	5	3
12/10/57	18	Calm	210	Calm	1.2	8.9	10.4	2	4
12/10/57	21	170	227	1.0	0.9	8.3	9.4	6	5

Table 3 – Comparison of observed and ERA40 met data at Watnall (53.0°N Latitude 1.25°W Longitude, Station Altitude: 117m)

		Silloth			Watnall		
		Observed	ERA-40	Difference	Observed	ERA-40	Difference
Date	Hour (GMT)	Mean sea level Pressure (mb)	Mean sea level Pressure (mb)	(mb)	Mean sea level Pressure (mb)	Mean sea level Pressure (mb)	(mb)
10/10/57	18	1015	1014	1	1015	1015	0
10/10/57	21	1015	1015	0	1015	1015	0
11/10/57	00	1015	1015	0	1016	1016	0
11/10/57	03	1015	1016	-1	1016	1016	0
11/10/57	06	1017	1016	1	1016	1016	0
11/10/57	09	1019	1018	1	1018	1017	1
11/10/57	12	1020	1020	0	1019	1019	0
11/10/57	15	1020	1021	-1	1020	1020	0
11/10/57	18	1022	1021	1	1022	1022	0
11/10/57	21	1024	1023	1	1024	1024	0
12/10/57	00	1024	1024	0	1025	1025	0
12/10/57	03	1024	1024	0	1026	1025	1
12/10/57	06	1024	1024	0	1026	1026	0
12/10/57	09	1025	1024	1	1028	1026	2
12/10/57	12	1024	1025	-1	1027	1027	0
12/10/57	15	1023	1023	0	1026	1026	0
12/10/57	18	1022	1022	0	1025	1024	1
12/10/57	21	1022	1022	0	1025	1025	0

Table 4 – Comparison of observed and ERA40 mean sea level pressure at Silloth and Watnall

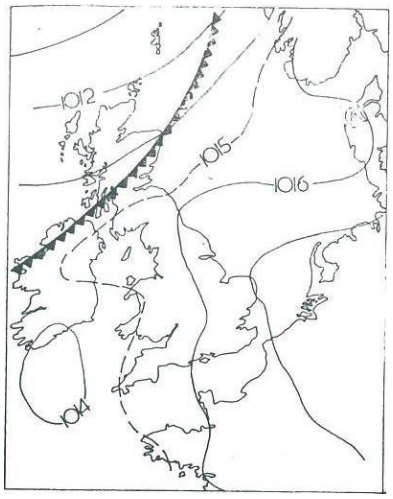
Wind direction is in broad agreement over the study period at both locations with winds mainly from the southwest to northwest sectors with calms observed at both met stations. Both the observed and ERA-40 data generally demonstrated light winds. These calm conditions may often be accompanied by large discrepancies in wind direction. Observed windspeeds increase at the end of the period at Silloth while the ERA-40 windspeeds remain around 3.0 ms^{-1}. Gridded temperature data were in broad agreement with the observed data at both locations. Cloud cover varied generally by up to a few octas between the two data sources.

It should be noted that at these windspeeds there could be a significant error in the windspeed reported at the ground based observation sites. This is because the anemometer start-up speed in the equipment used at the time was typical around 2ms^{-1}.

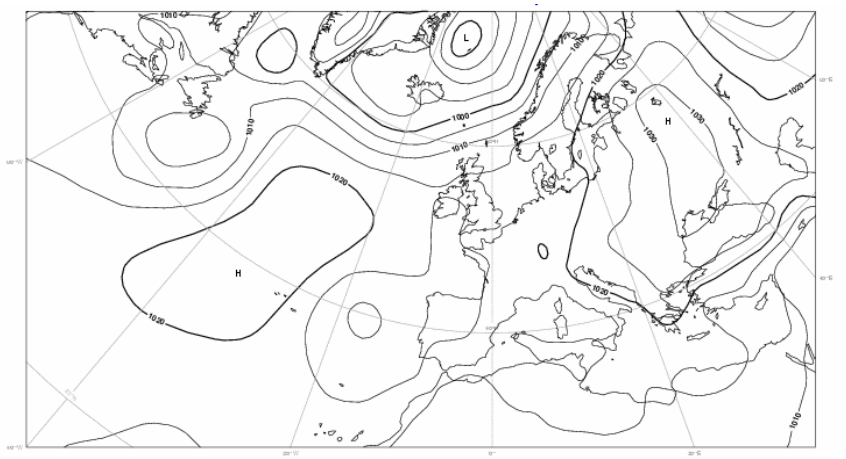
The assimilations scheme used in ERA-40 will use a number of sources of information to determine windspeed and direction. A key component will be mean sea level pressure and Table 4 shows modelled and observed values for this element. As can be seen there is a much closer agreement between these values than between windspeed and direction in Tables 2 and 3.

For the two sites compared above observed windspeeds tend to be slightly higher than the modelled wind field. If this anomaly is consistent across the rest of the domain then the impact on the resultant air concentrations from the model will probably be slightly higher and a little less dispersed than in reality.

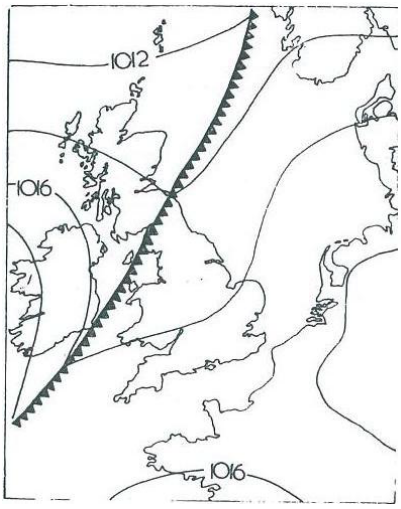
Synoptic charts from *(Crabtree 1959)* and those produce by the ERA-40 re-analysis (available from ECMWF website http://data.ecmwf.int/data/d/era40_daily/) are compared in Figure 1. The ERA-40 re-analysis charts cover a much larger area than the synoptic charts with contour intervals of 5 mbar whereas the synoptic charts have a contour interval of 2 mbar. However, the plots both show general pressure patterns which can be compared.



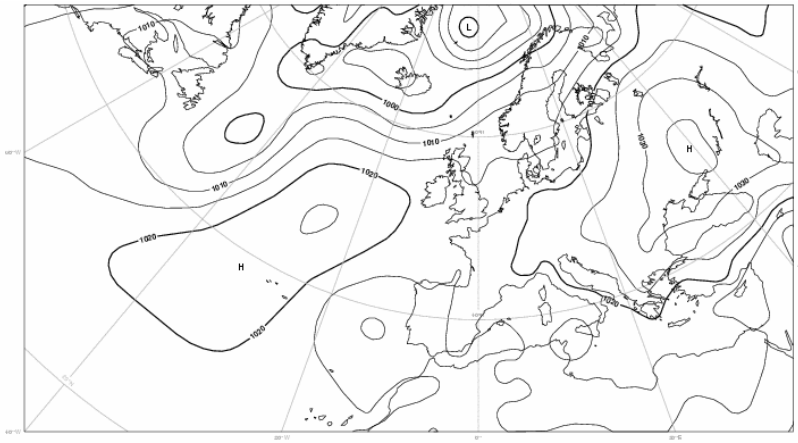
Crabtree (1959)
1200 GMT 10th October 1957



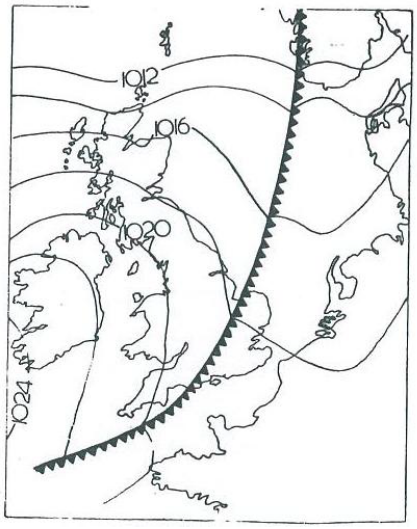
ERA-40 data
1200 GMT 10th October 1957



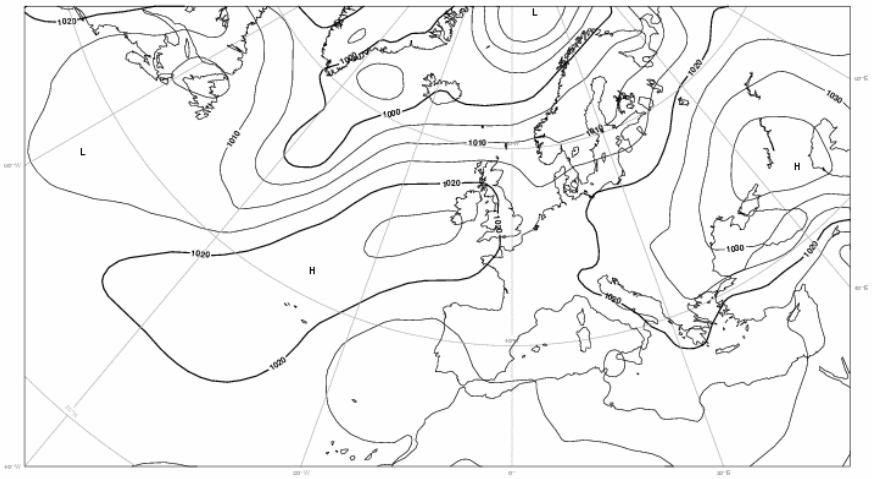
Crabtree (1959)
0000MT 11h October 1957



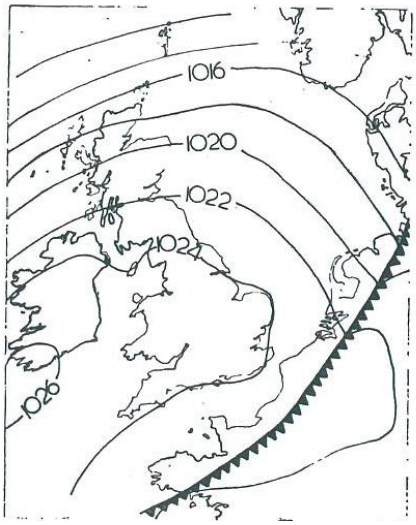
ERA-40 data
0000MT 11th October 1957



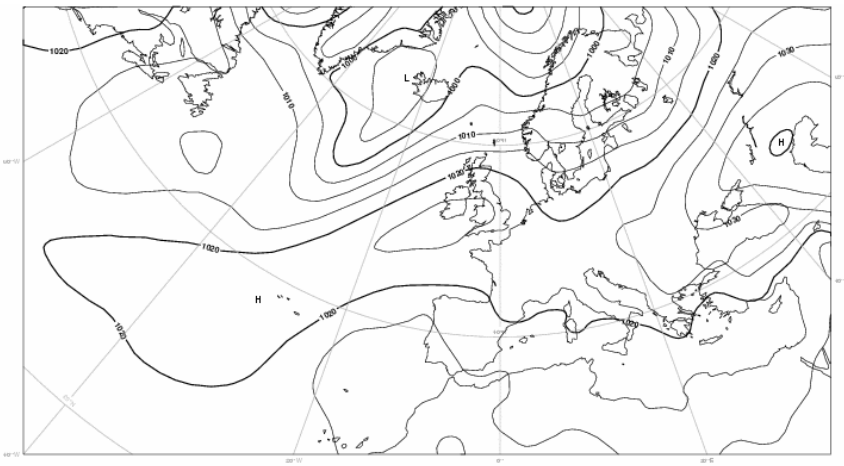
Crabtree (1959)
1200 GMT 11th October 1957



ERA-40 data
1200 GMT 11th October 1957



Crabtree (1959)
0000 GMT 12th October 1957



ERA-40 data
0000 GMT 12th October 1957

Figure 1 Comparison of synoptic charts in Crabtree (1959) and pressure plots of ERA-40 data

It can be seen from Figure 1 that the pressure fields in the ERA-40 data closely match that of the synoptic charts therefore the synoptic situation including movement of fronts, wind speeds and directions within the NAME model run will be similar to those experienced at the time of the incident.

4.0 Results

4.1 Windspeed

In attempting to deduce the amount of Iodine-131 crossing a line drawn from Liverpool to Flamborough Head (Figure 1), *Crabtree (1959)* investigated air activity data for Lancashire and Yorkshire. This line was chosen as it runs approximately perpendicular to the movement of the radioactive plume. Air concentration data along 30km of the line were used to deduce the mean Iodine-131 activity at the surface a along the line during the period 09:00 on the 10/10/57 to 09:00 on the 12/10/57.

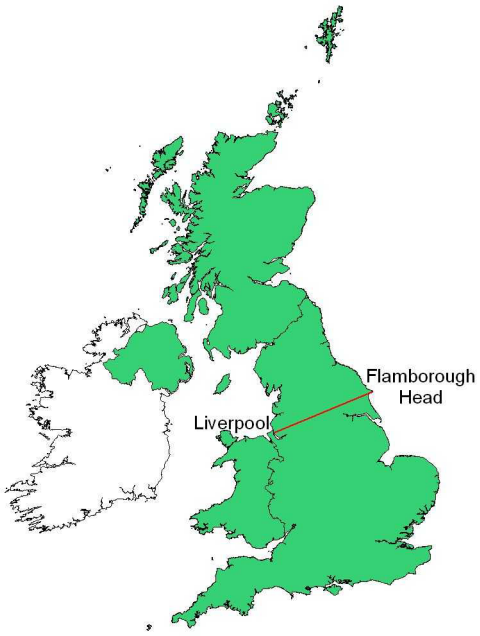


Figure 1: Liverpool to Flamborough Head line used by Crabtree

In addition to the air concentration, depositions and plume movement calculations performed by NAME, information regarding the meteorological situation was also retrieved directly from the ERA-40 dataset. Forty-two points along the Liverpool to Flamborough Head line were chosen to extract model windspeed and direction data.

The wind data was then interpolated to measurement station locations listed Table 4 below for the period when activity crossed the line. The flux was then calculated using column air concentrations, windspeed, wind direction and angle of the wind to the perpendicular, for each hour that the model predicted activity at the measurement stations. The hourly flux were totalled and divided by the total of the column concentrations to calculate an effective mean wind component to the line of 4.8ms^{-1}. This compares well with Crabtree's estimate of 5.0ms^{-1}.

4.2 Air concentrations

Air concentration calculations were extracted at receptor points for a number of locations along the Liverpool to Flamborough Head Line and details of the plume's predicted initial arrival time is detailed in Table 4.

Site	Latitude	Longitude	Initial plume arrival October 1957
Liverpool	53.4°N	3.1°W	13:00 12th
St Helens	53.5 °N	2.7 °W	13:00 11th
Warrington	53.4 °N	2.6 °W	13:00 11th
Preston	53.8 °N	2.7 °W	10:00 11th
Sale	53.4 °N	2.3 °W	13:00 11th
Bolton	53.6 °N	2.4 °W	12:00 11th
Salford	53.5 °N	2.3 °W	12:00 11th
Manchester	53.5 °N	2.2 °W	12:00 11th
Burnley	53.8 °N	2.3 °W	10:00 11th
Keighley	53.9 °N	1.9 °W	09:00 11th
Sheffield	53.5 °N	1.5 °W	12:00 11th
Bradford	53.8 °N	1.7 °W	10:00 11th
Batley	53.7 °N	1.6 °W	11:00 11th
Leeds	53.8 °N	1.5 °W	10:00 11th
Doncaster	53.5 °N	1.1 °W	12:00 11th

Table 4. Receptor locations and time of initial arrival of the modelled plume

Table 4 shows that the modelled plume did not reach as far west as Liverpool on its initial track. Figures 8 to 12 show that the plume passed to the north and east of the city. It finally reached Liverpool at 13:00 on 12th October 1957 (Figures 16 and 17), after the plume circulated around much of the south of England and travelled back north to the Midlands.

Radioactivity values recorded at locations in Europe are published in *Stewart, et al (1961)*. These values were mainly recorded over a 24 hour period therefore cannot be used to pin point plume arrival times. They do however provide a window of activity against which the air concentrations predicted by NAME can be compared. Measured activity was available at a number of sites across the UK and Europe. As this study is investigating the initial track of the plume Liverpool, Warrington, Manchester and Leeds have been chosen for comparison. Table 5 contains details of the comparison.

Location Time filter changed	Date of Measured Activity in Oct 1957	Timing of Modelled Activity in Oct 1957
Liverpool	25/09/1957- 23/10/1957	13:00 12th-09:00 13th
Warrington 1200 GMT	10th -11th 11th-12th 12th-14th	13:00 11th-19:00 11th 13:00 12th - 10:00 13th
Manchester 1100 GMT	10th-11th 11th-12th 12th-13th	11:00 11th – 22:00 11th 13:00 12th – 13:00 13th
Leeds 1200 GMT	10th-11th 11th-12th 12th-14th	10:00 11th-14:00 11th 15:00 12th -13:00 13th

Table 5 Comparison of measured activity against predicted activity

Table 5 illustrates that the time window of activity at the sites with measured activity across the Liverpool to Flamborough Head line are in broad agreement with the timings of plume arrival predicted by NAME.

4.3 Boundary Layer Height

In *Crabtree (1959)* it was assumed that the maximum boundary height was 1,500m. The maximum boundary layer height, calculated by NAME, at specific times over the entire modelled grid are shown in Table 6.

Time and Date	Maximum Boundary Layer Height (m)
1630UTC 10/10/1957	889
1800UTC 10/10/1957	931
2100UTC 10/10/1957	1040
0000UTC 11/10/1957	1145
0300UTC 11/10/1957	1049
0600UTC 11/10/1957	954
0900UTC 11/10/1957	933
1200UTC 11/10/1957	1100
1500UTC 11/10/1957	989
1800UTC 11/10/1957	1048
2100UTC 11/10/1957	915
0000UTC 12/10/1957	827
0300UTC 12/10/1957	770
0600UTC 12/10/1957	756
0900UTC 12/10/1957	888
1200UTC 12/10/1957	**1182**
1500UTC 12/10/1957	1105
1800UTC 12/10/1957	1125
2100UTC 12/10/1957	1065
0000UTC 13/10/1957	1042
0300UTC 13/10/1957	926
0600UTC 13/10/1957	1008
0900UTC 13/10/1957	879
1200UTC 13/10/1957	1084
1500UTC 13/10/1957	745
1700UTC 13/10/1957	658

Table 6. Maximum modelled boundary layer height

Boundary layer height varies over time and location as atmospheric conditions change. During the time period covered by the NAME run (16:30 on 10/10/1957 to 17:00 on 13/10/1957) the NAME calculated boundary layer height did vary with time and location giving an average of 485m. Table 6 shows that the calculated maximum boundary layer height over the entire grid, was 1,182m. This occurred at 12:00 on 12/10/1957 at 56^{o}N Lat 4^{o}W Lon.

Crabtree makes reference in his paper to upper air data recorded at Liverpool, Aldergrove and Hemsby. This ‘indicated that the air ahead of the front was mainly stable, and that the air behind the front was neutral or slightly unstable up to about 1,500m with an inversion above’, the upper air ascents took place at 11:00 on the 11th October. Table 7 shows boundary layer height estimated by NAME for the closest receptor point and time interval to the three locations at 12:00 on 11th October 1957,

Site	Boundary Layer Height (m)
	12:00 11/10/1957
Aldergrove	905
Liverpool	927
Hemsby	171

Table 7 Modelled boundary layer height on 11/10/1957

The front had crossed Aldergrove and Liverpool by 12:00 on the 11th October but did not reach Hemsby until later on the 11th, *Crabtree (1959)*. This is consistent with the stable conditions showing lower boundary layer ahead of the front. A more detailed description of the synoptic situation can be found in *Nelson et al (2005)*.

Given the inherent difficulties in assessing boundary layer height, this is general agreement with Crabtree's estimate of 1500m, though obviously somewhat lower. There are a limited number of vertical levels within the ERA-40 dataset and this will give rise to some errors in calculating boundary layer heights. The NAME model will take broad scale met structures into account such as large scale topographical features. It will not however encompass small scale features including land/sea breezes and small scale topographically induced winds.

More details about the NAME model can be found in *Ryall et al (1998)*.

4.4 Effective Plume Height

Another method of assessing the vertical spread of a plume is to calculate the effective plume height (Equation1), the height of the centreline of the plume above ground level.

$$H_{eff} = \frac{\int_0^{h_{\max}} c\,dz}{c_{z=0}} \qquad (1)$$

where z is height above ground, c is concentration and h_{max} denotes the top of the plume. H_{eff} is the concentration weighted average over the line.

The values in *Crabtree (1959)* produce a figure of 860m. This compares well to a mean value of 1,000m for 14 points across England starting at Liverpool and ending at 55.03° N Latitude 3.97° E Longitude during passage of the plume.

4.5 Model results

Figures 2 to 19 show air concentrations of Iodine-131 within the boundary layer at three hourly intervals during the modelled period.

They illustrate the movement of the plume starting with the initial release at 16:30 on 10/10/1957 (Figure 2) until 21:00 on 12/10/1957 (Figure 19).

Figures 3 to 6 show that the modelled plume initially tracked northeastwards. By 06:00 on the 11th (Figure 6) it extended across northern England. It began to track south while extending further into the North Sea at 09:00 on the 11th (Figure 7). It missed Liverpool on its initial track, moving to the north and east of the city (Figures 8 to 12). By 18:00 on the 11th (Figure 10) it had extended into the North Sea up to 4° E Long. Figure 13 illustrates that the plume had reached the south of England by 03:00 on the 12th.

Re-circulation started to take place from 09:00 on the 12th (Figure 15), causing the plume to track northwards, back up the country, reaching Liverpool at 13:00 on the 12th (Table 2, Figures 16 and 17).

Crabtree calculated the amount of Iodine-131 crossing the line using concentration data for the time period 48 hours starting at 09:00 on 10/10/1957. The model shows the entire plume crossed the Liverpool to Flamborough Head line (including its extrapolation over the North Sea) only once during this period.

It is worth noting that the deposition process was simulated within this model run and together with radioactive decay will contribute towards the plume's depletion over time. It is recognised that this contributes to the uncertainty in concentration value particularly in the older parts of the plume.

5.0 Conclusions

Crabtree made a number of assumptions in his 1957 paper. Each of these has been tested within this study. The first being a maximum boundary layer height of 1500m. This is in general agreement with the results of this study with a maximum boundary layer height of 1182m over the entire receptor grid. The difference may be due to the methods used to calculate it. Crabtree made his estimation from radiosondes (upper air ascents) carried out at Liverpool, Aldergrove and Hemsby. NAME, however, calculated the boundary layer height from the met data for each point on the receptor grid.

The effective plume height was calculated giving a value of 860m using Crabtree's assumptions and 1000m when using data predicted by the model. These are in broad agreement.

The second assumption made was that the plume was 120km wide as it crossed the Liverpool to Flamborough Head line. In this study, the modelled plume did not reach as far west as Liverpool on its initial track but extended over the North Sea out to 4° E Longitude. The plume tracked southwards initially but then swept back northwards in a re-circulation movement, finally reaching Liverpool on 12th October. The main differences were therefore the extent of both the eastern and western edges of the plume.

In his paper Crabtree also estimated that the average perpendicular windspeed along the Liverpool to Flamborough Head line, during the passage of the plume, was about 5.0ms^{-1}. The ERA-40 met data used within this study gives a perpendicular windspeed of 4.8ms^{-1} when averaged along the line over the period when activity was predicted by the model. This is therefore in agreement with Crabtree's estimate.

A further study is planned to assess the long range transport of the radionuclides including a more detailed comparison of plume arrival times against European monitoring data and an attempt to define air concentrations across Europe.

6.0 References

Arnold, L.M., (1995). Windscale 1957. Anatomy of a Nuclear Accident. Macmillan, London.

Chamberlain, A.C. (1959). Deposition of iodine-131 in Northern England in October 1957. Quart. J. R. Met. Soc., **85**, 352-361.

Chamberlain, A.C. (1996). Emissions from Sellafield and activities in soil. Sci.Total Environ. **177**, 259 – 280.

Chamberlain, A.C. and Dunster, H.J. (1958). Deposition of radioactivity in North-West England from the accident at Windscale. Nature, Lond., **182** 629-630.

Crabtree, J. (1959). The travel and diffusion of the radioactive material emitted during the Windscale accident. Quart. J. R. met. Soc., **85**, 362.

Crick, M.J. and Linsley G.S. (1984). An assessment of the radiological impact of the Windscale reactor fire, October 1957. Int J Radiat Biol **46** 479-506.

Dunster, H.J., Howells, H. and Templeton, W.L. (1958). District Surveys Following the Windscale incident, October. Proc.II int. Conf. Peaceful Uses Atomic Energy, **18**, 296.

Gibson R, Kallberg P and Uppala S. (1997): The ECMWF Re-Analysis (ERA) Project, ECSN Newsletter 5: 11-21

Nelson, N., Kitchen K. P. and Maryon, R. H.(2005) A Study of the Movement of Radioactive Material Discharged during the Windscale Fire in October 1957, under review

Penney W (1957). Accident at Windscale No. 1 Pile on 10th October 1957. Cmnd 302. HMSO, London.

Ryall, D.B. and Maryon, R.H. (1998) Validation of the UK Met Office's NAME model against the ETEX data. Atmospheric Environment, **32**, 4265-4276

Stewart, N.G. and Crooks,R.N. (1958). Long-range travel of the radioactive cloud from the accident at Windscale. Nature, Lond., **182** 627-628.

Stewart, N.G., Crooks, R.N. & Fisher, E.M.R. (1961). Measurements of the Radioactivity of the Cloud from the Accident at Windscale: Data submitted to the I.G.Y. UK Atomic Energy Authority – Research Group Memorandum.

Webster, H.N and Thomson,D.J. (2002) Validation of a Lagrangian model plume rise scheme using the Kincaid data set. Atmospheric Environment, **36**, 5051-5062

Weerasekara N S, Garland J A and Lockwood F C, Estimate of the Chimney Temperature and Flow Rate during the Pile 1 Fire at Windscale, October 1957, December 2004, Journal of the Energy Institute, 77 pp 76-81.

7.0 Acknowledgements

This work was sponsored by British Nuclear Fuels plc, Warrington, UK.

Appendix A – Model Plots Showing 1 hour Average Air Concentrations

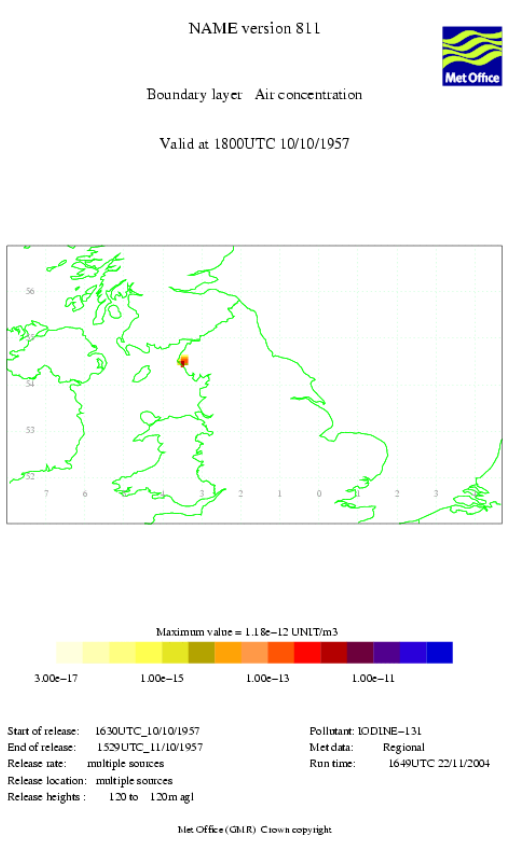


Figure 2: Air concentration in Boundary Layer at 1800hr on 10/10/1957

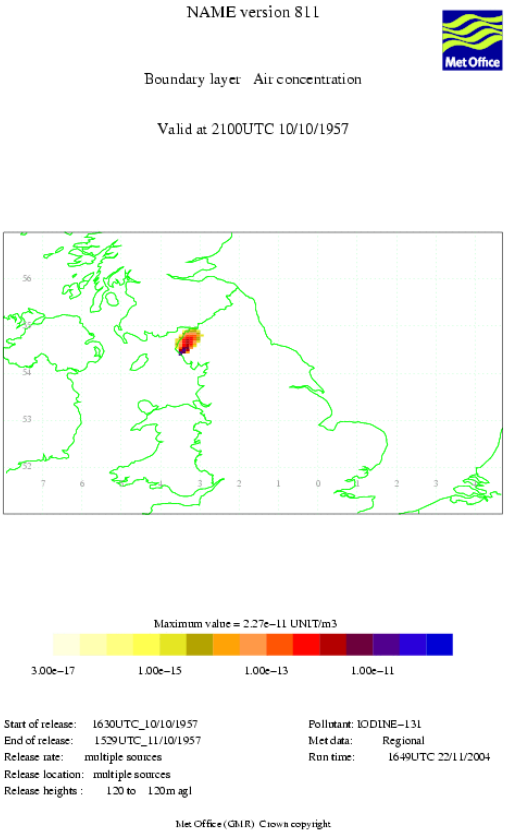


Figure 3: Air concentration in Boundary Layer at 2100hr on 10/10/1957

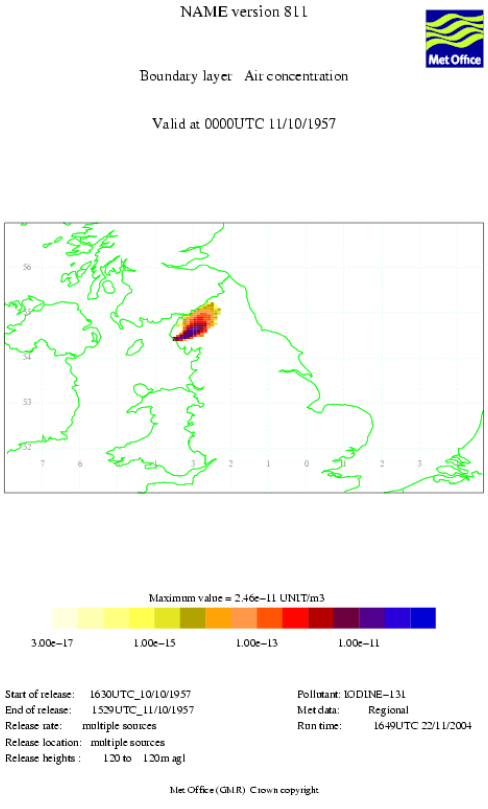


Figure 4: Air concentration in Boundary Layer at 0000hr on 11/10/1957

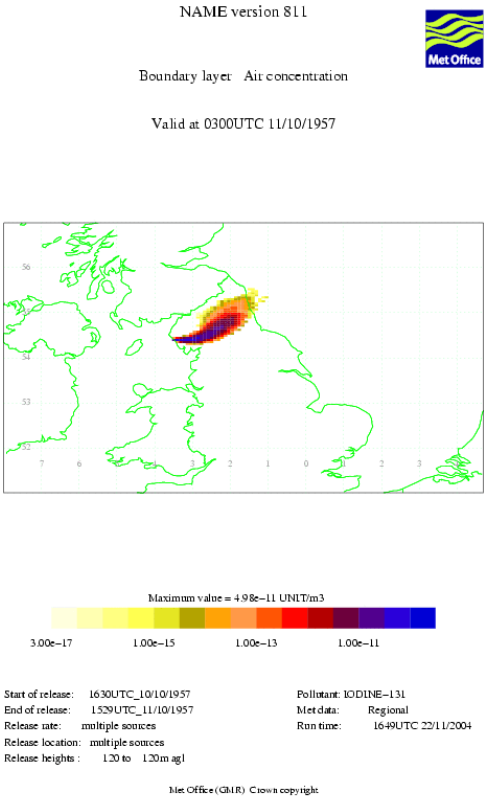


Figure 5: Air concentration in Boundary Layer at 0300hr on 11/10/1957

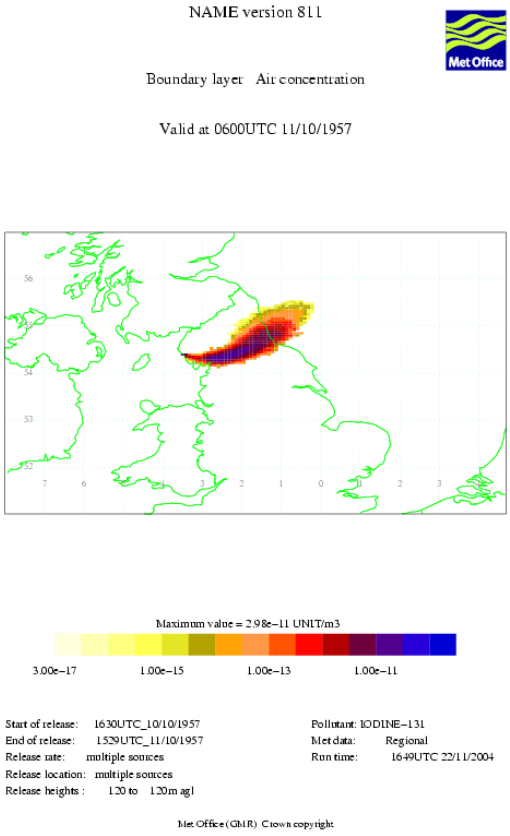


Figure 6: Air concentration in Boundary Layer at 0600hr on 11/10/1957

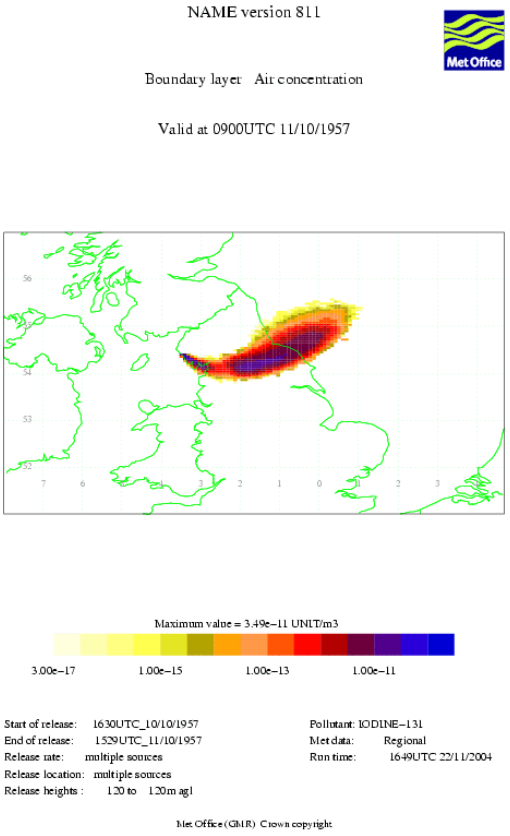


Figure 7: Air concentration in Boundary Layer at 0900hr on 11/10/1957

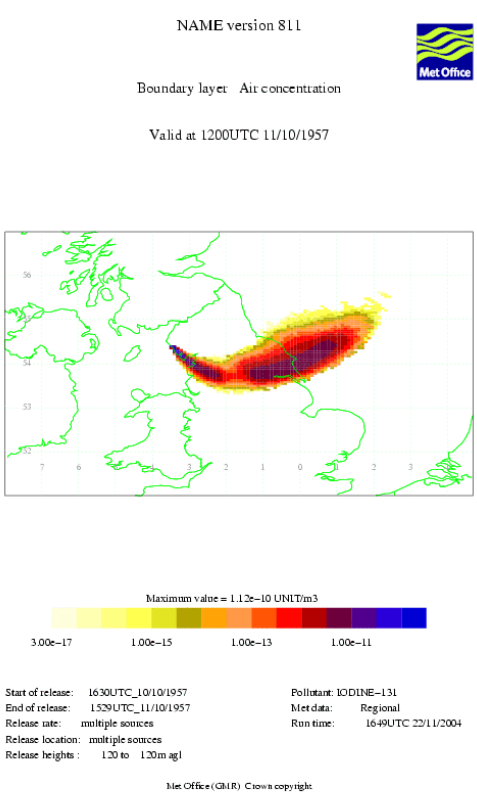


Figure 8: Air concentration in Boundary Layer at 1200hr on 11/10/1957

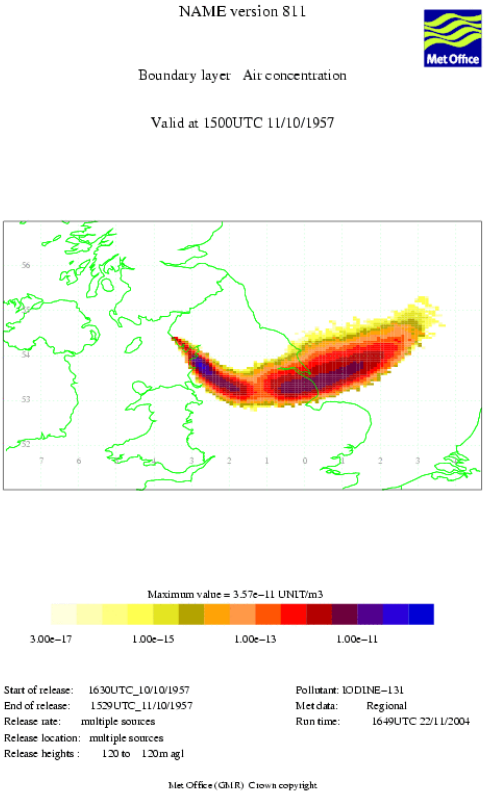


Figure 9: Air concentration in Boundary Layer at 1500hr on 11/10/1957

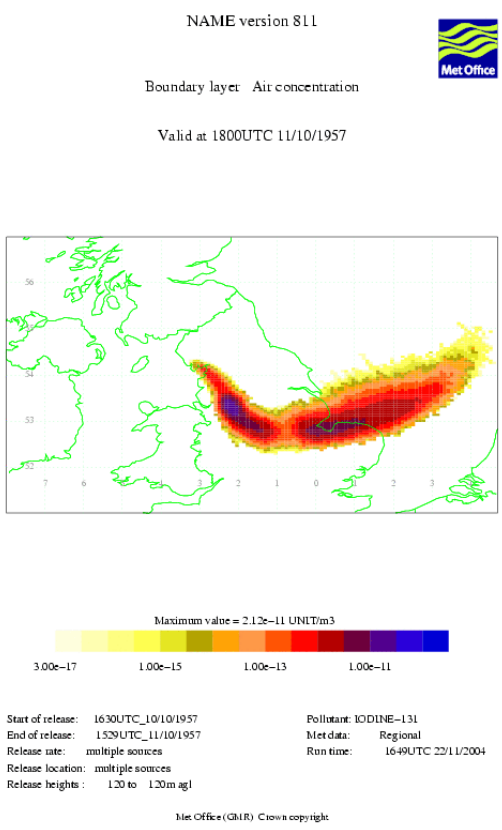


Figure 10: Air concentration in Boundary Layer at 1800hr on 11/10/1957

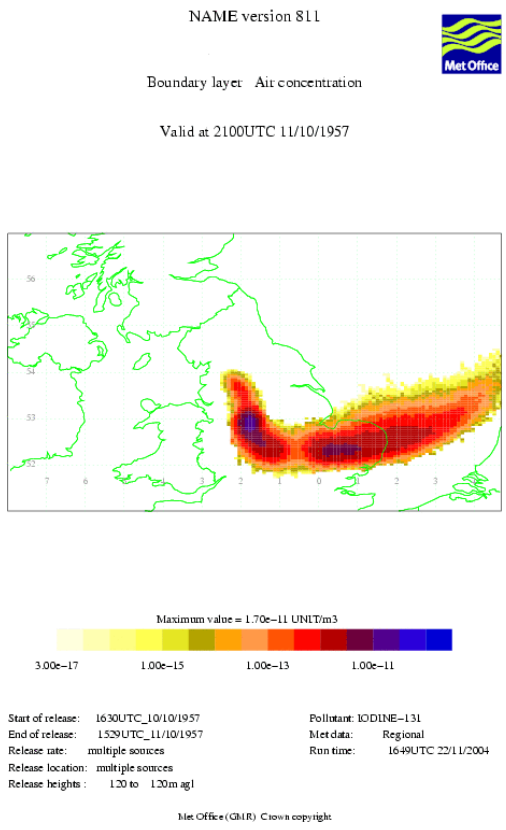


Figure 11: Air concentration in Boundary Layer at 2100hr on 11/10/1957

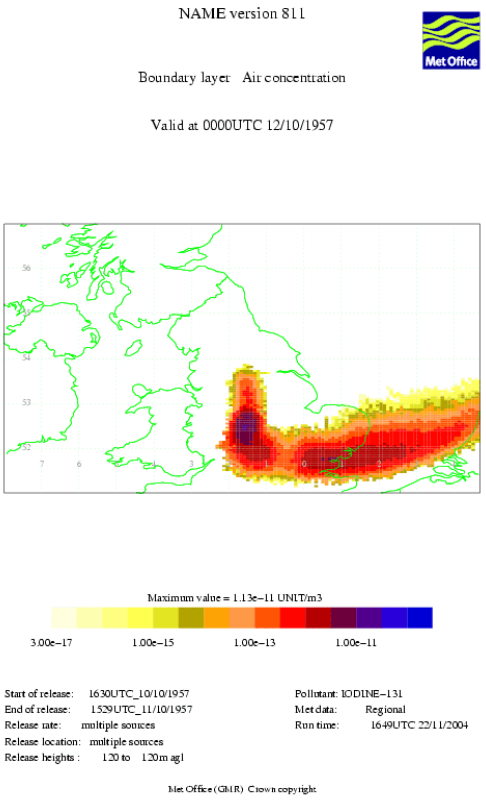


Figure 12: Air concentration in Boundary Layer at 0000hr on 12/10/1957

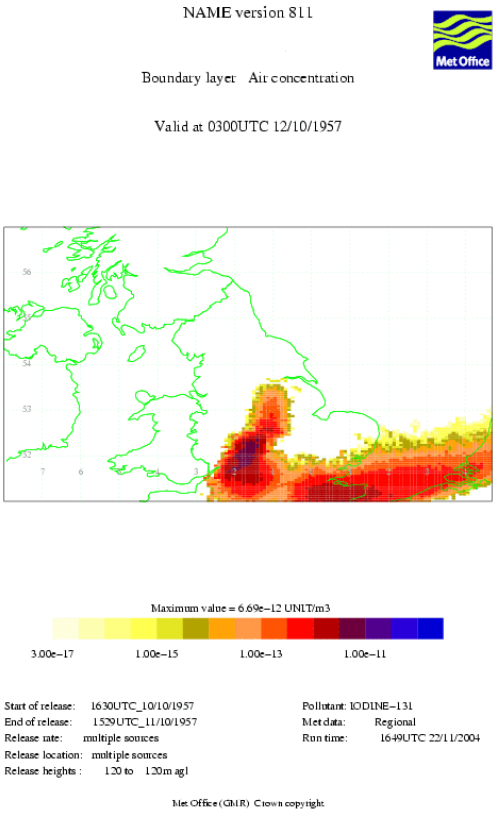


Figure 13: Air concentration in Boundary Layer at 0300 on 12/10/1957

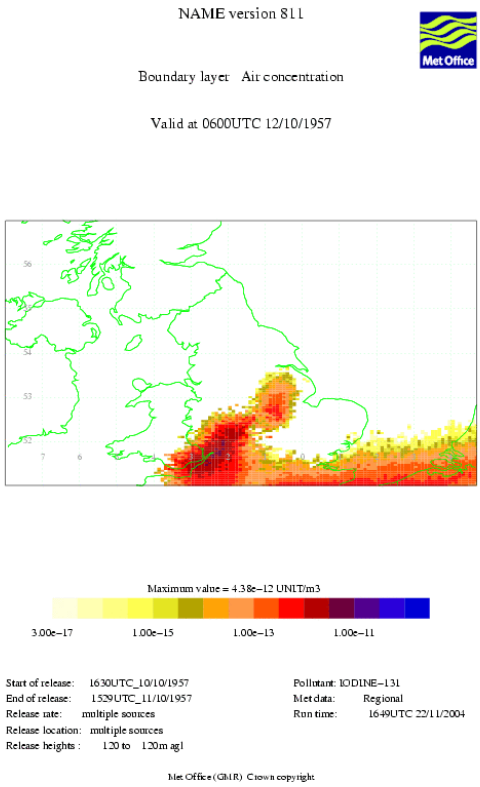


Figure 14: Air concentration in Boundary Layer at 0600hr on 12/10/1957

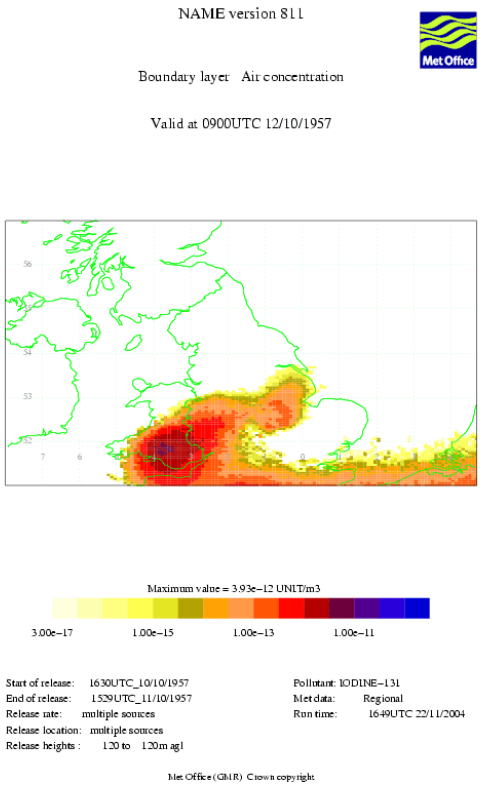


Figure 15: Air concentration in Boundary Layer at 0900 on 12/10/1957

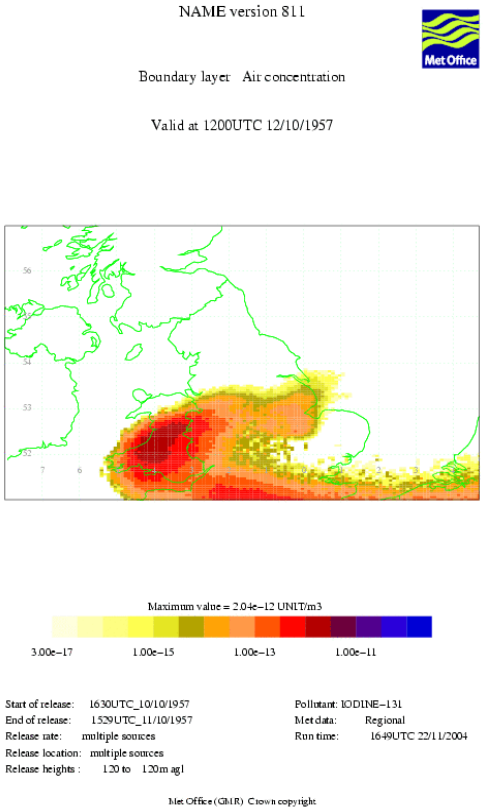


Figure 16: Air concentration in Boundary Layer at 1200hr on 12/10/1957

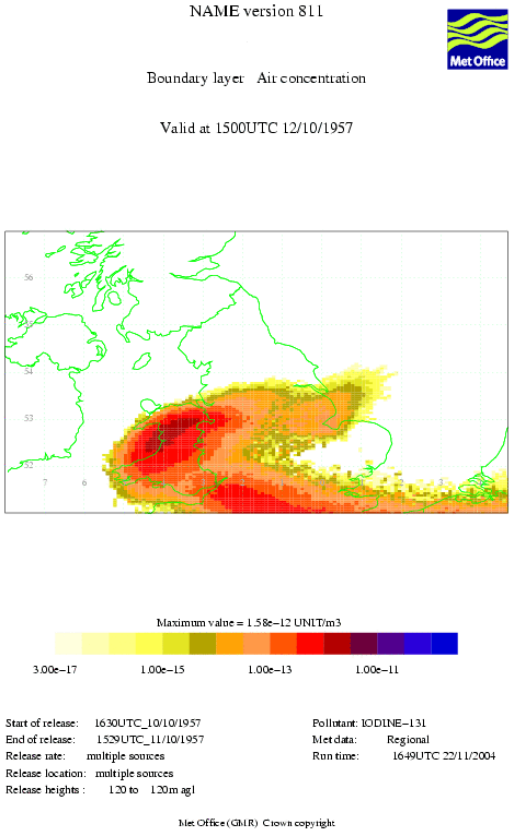


Figure 17: Air concentration in Boundary Layer at 1500 on 12/10/1957

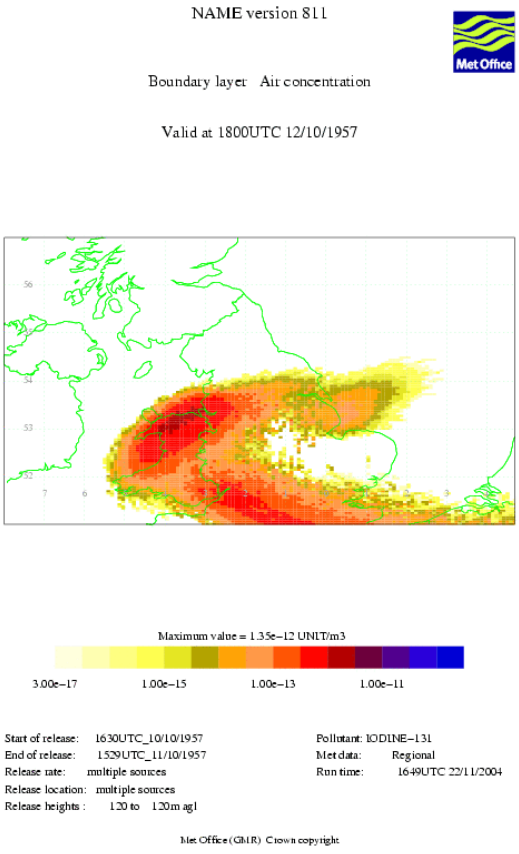


Figure 18: Air concentration in Boundary Layer at 1800hr on 12/10/1957

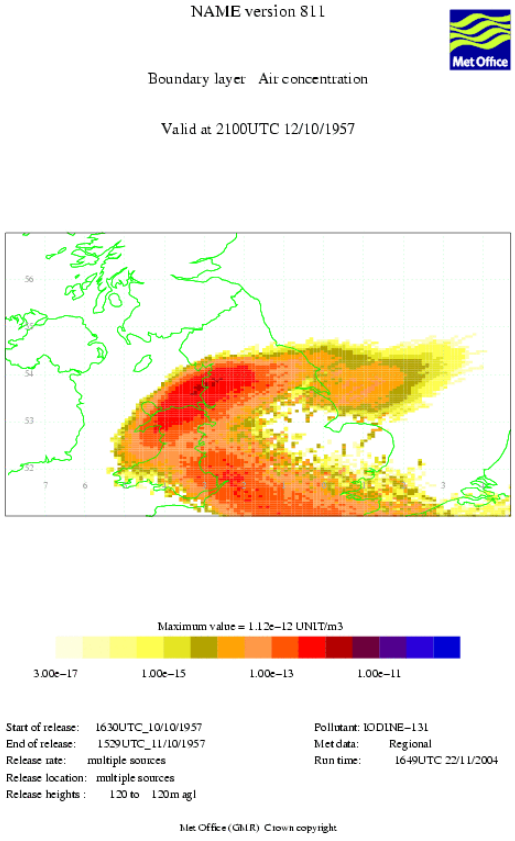


Figure 19: Air concentration in Boundary Layer at 2100 on 12/10/1957